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MICROFABRIC EVIDENCE FOR PODZOLIC SOIL INVERSION BY SOLIFLUCTION PROCESSES

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ABSTRACT

The inverted stratigraphy of a turf-banked solifluction lobe formed in a podzol in northern Norway is presented. Additional evidence for soil inversion takes the form of an inverted micromorphological profile. Encircling silt cappings, and related microstructures, are described from thin sections. This microstructure is created by grain rotation during the spring thaw of sediment when excess pore water pressures promote viscous flow. Melting ice lenses release silt which is then trapped on all sides of detrital grains. The presence of these microstructures in the near-surface and base of the solifluction lobe, but not at mid-depths, supports the notion of an inverted stratigraphy.

KEY WORDS solifluction; micromorphology; silt cappings; alpine podzols; Okstindan

INTRODUCTION

As part of a wider investigation into cold climate Holocene slope processes and climatic change, micromorphological studies were conducted on sediments from turf-banked solifluction lobes in Okstindan, north Norway (Figure 1). Most observations concerning microstructures indicative of soil freezing and solifluction processes have been made on samples obtained from field investigations, and include vesicles, banded fabrics, oriented detrital grains, silt cappings on the upper surfaces of grains, silt droplets, fragipans and shear surfaces (e.g. Harris and Ellis, 1980; Harris, 1985; Van Vliet-Lanoë, 1985). Similar microstructures have been reproduced in laboratory simulation experiments of mass movement and soil freezing (Coutard and Mücher, 1985; Coutard *et al.* 1988; Van Vliet-Lanoë *et al.*, 1984).

This paper describes an inverted stratigraphy and micromorphological profile from solifluction sediments in northern Norway. The predominant microstructure observed in the thin sections is termed an 'encircling silt capping' and has hitherto received little attention.

METHODS

Solifluction lobes in Okstindan, developed in podzolic soils overlying Late Weichselian till, are typically 0·5–1·0 m in height and possess lobe treads approximately 8–10 m in length. A trench (6·0 m × 1·5 m × 1·0 m) was dug by hand along the principal axis of a solifluction lobe at 740 m a.s.l. (Figures 1 and 2). Soil profiles were logged at 0·5 m intervals along the lobe section using the criteria of Hodgson (1974). Each soil horizon (sediment unit) was sampled for grain size analysis and determination of Atterberg limits. Undisturbed oriented samples were taken from each horizon by inserting steel Kubiena boxes (80 × 65 × 40 mm) with sharpened leading edges into a freshly cleaned face of the trench. On returning to the laboratory, the lids were removed and samples left to air dry for two weeks. Each sample was then impregnated with crystic resin under vacuum conditions, adopting the procedures of Lee and Kemp (1993). Oriented thin sections were cut from the impregnated blocks in the vertical plane, and polished to approximately 40 μm in thickness

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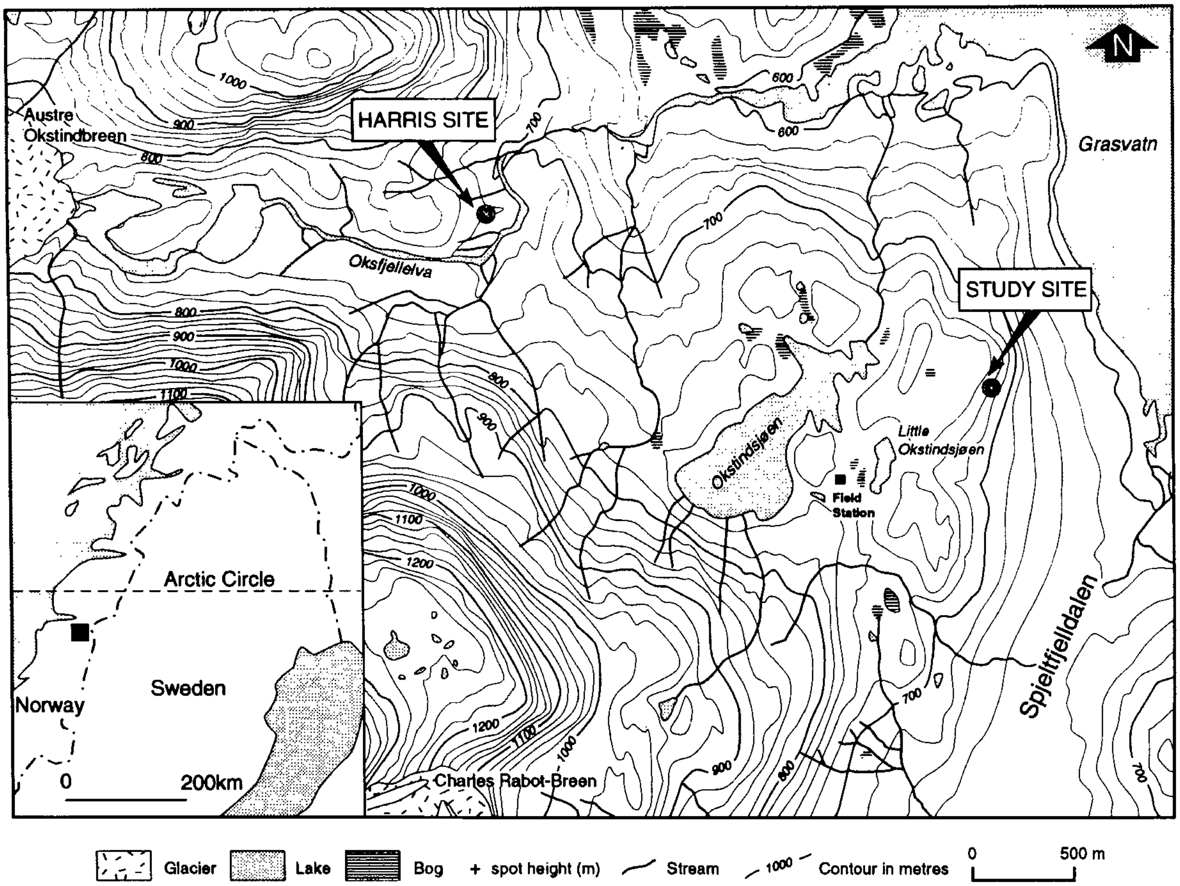

Figure 1. Location of solifluction lobe study area, at 740 m a.s.l. in Okstindan, north Norway. Note the position of the ground thermal regime study site of Harris (1974), where solifluction rate/depth measurements were also monitored

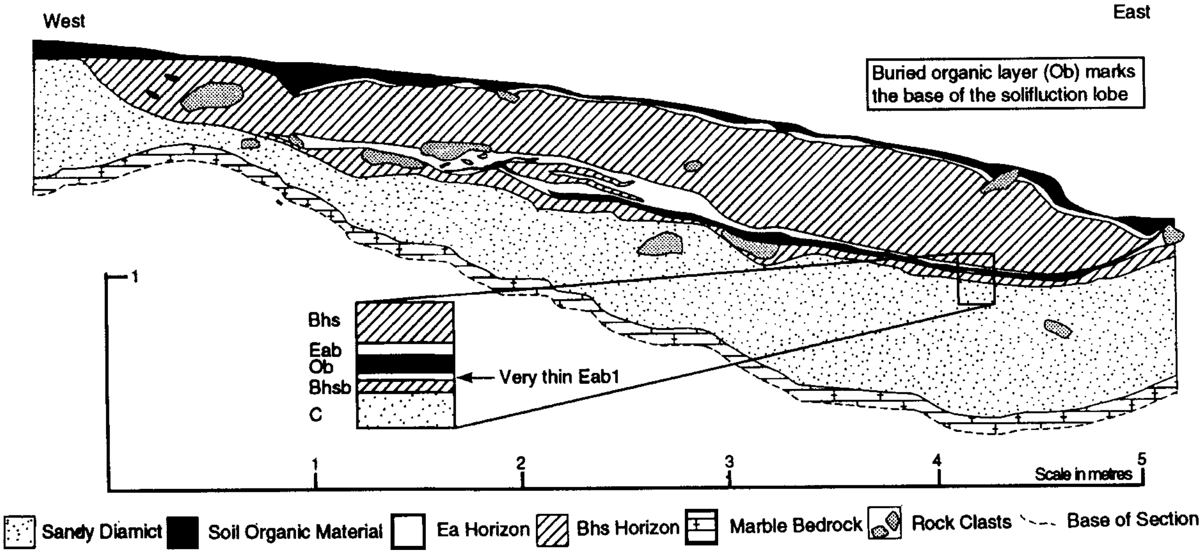

Figure 2. Solifluction lobe stratigraphy of a turf-banked solifluction lobe at the study site. Note inverted and buried eluvial albic (Eab and Eab1 respectively) and organic (Ob) horizons in a humo-ferric podzol overlying a Late Weichselian silty-sandy till of Swedish provenance

Table I. Radiocarbon age estimates from soil organic horizons in podzols buried by solifluction, Spjeltfjelldalen, Okstindan, Norway. Note that the assays were run on bulk samples, and thus the results should be treated with caution (Fenwick, unpublished data)

Sample	Lab. no.	Material	^{14}C age $\pm$ 1σ	$\delta^{13}C$ (‰)
MR1	SRR-1303	Soil organics	1100 ± 40	−26·0
MR3	SRR-1305	Soil organics	1305 ± 40	−26·2

on a Logitech PM 2 lapping machine. Observations were made using a transmitted light petrological microscope.

LOBE STRATIGRAPHY AND PEDOLOGY

The humo-ferric podzols in Okstindan possess a thick (0·10 m) vegetation mat (Ah horizon) consisting of *Vaccinium myrtillus*, *Empetrum nigrum* and *Betula nana*. High organic productivity enables chelating agents to mobilize iron and aluminium, producing a distinct light grey (5Y 7/1, moist Munsell notation) eluvial (Ea) horizon approximately 0·02 m in thickness (Figure 2). A very dusky red (10R 2/2) podzolic illuvial (Bhs) horizon, approximately 0·50 m in thickness, underlies this. It is this horizon that has undergone solifluction (Figure 2). Beneath the Bhs horizon, another grey (5Y 7/1) eluvial horizon (Eab) 0·02 m thick is encountered, which is evidence to support the notion that the soil has been *inverted*. Its lower boundary is sharply defined by an organic-rich (Ob) horizon. The organic matter is peat-like in appearance, contains fragments of degraded rootlets and virtually no sediment grains. This buried organic layer varies in thickness along the trench section from less than 0·01 m to a maximum of 0·08 m. The layer therefore represents the former vegetated land surface prior to burial by soliflucted podzolized sediments, and is unlikely to be the Bh horizon of a partially eroded soil from a previous phase of pedogenesis. A thin (0·30 m), 'normal way up', relatively undisturbed podzol soil occurs beneath this (Figure 2). The organic horizon of the soil has been 'welded' onto the Ob horizon of the inverted podzol, though the precise contact is not clear, probably as a result of compaction from the sediment overburden. The presence of an eluvial horizon (Eab1) in this normal buried podzol is barely perceptible along most of the trench section, reaching only 0·01 m in thickness (Figure 2). The soil parent material (C) is a Late Weichselian olive brown (2·5Y 4/4) silty-sandy till. The till is approximately 0·50–0·75 m in thickness near the lobe front but thins to only 0·10 m where the marble bedrock rises at the back upslope limits of the solifluction lobe. The till unit lies unconformably on the Marble Member of the Lille Okstindsjöen Formation (Reynolds, 1978).

Potentially, the timing of soil inversion by solifluction can be established by intensively dating the buried organic soil horizon (Ob). A radiocarbon dating programme to establish the rates, timing and duration of Holocene solifluction phases at this and other sites in Okstindan is currently in progress, and the results will be presented on a future occasion. However, unpublished radiocarbon age estimates (Table I) obtained from a podzol buried by solifluction on the same slope as the lobe discussed here, indicated that the initiation of solifluction was probably of late Holocene (Neoglacial) age (I.M. Fenwick, pers. comm.). Unfortunately, these are crude age estimates only, because the assays were conducted on *bulk* organic soil samples, immediately before the deficiencies of such a strategy became apparent (Matthews, 1980, 1993). Given the close proximity of the soils investigated by Fenwick to the site discussed here, it is concluded that the solifluction which has inverted the podzol soil was probably of Neoglacial age as well, though further age estimates are required before this can be resolved in detail.

Grain size data (Figure 3) illustrate that the lobe sediments are silty sands. All but one of the data points fall within Harris' (1987) textural envelope for active solifluction sediments. Furthermore, Atterberg limits all fall within the envelope for active solifluction (Figure 4). The sediments from Okstindan are therefore classified as cohesionless, possessing only frictional strength. Solifluction lobes developed in these podzol soils move downslope in a 'caterpillar-track' fashion during the spring thaw phase when the sediment liquid

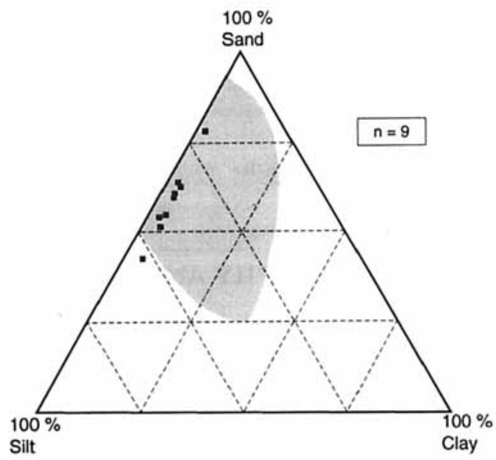

Figure 3. Ternary plot of sand–silt–clay for the matrix component of solifluction sediments in Okstindan. Note that all but one of the points fall within Harris' (1987) textural envelope for active solifluction

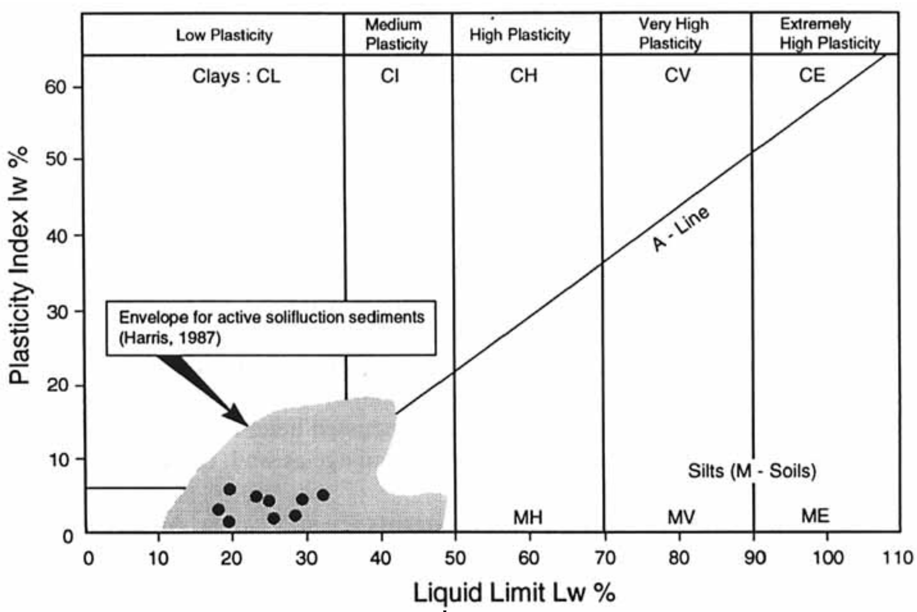

Figure 4. Plasticity chart illustrating inorganic silts with low plastic and liquid limits. Note that all points fall within Harris' (1987) envelope for active solifluction

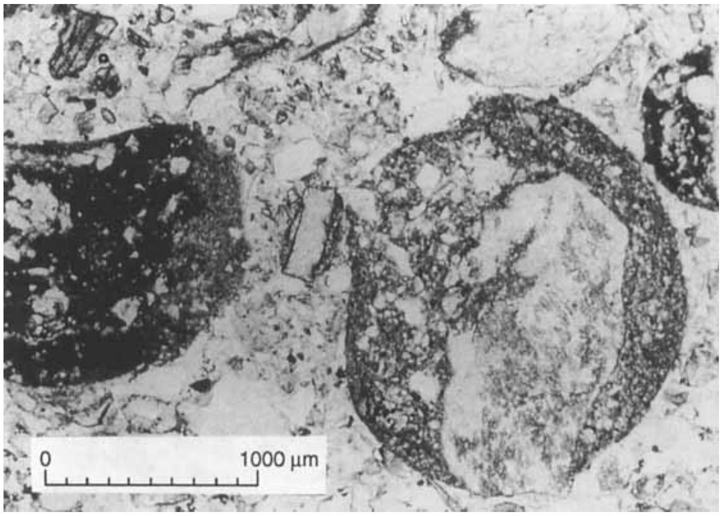

Figure 5. Thin section photomicrograph of an encircling silt capping (matrix coating) formed by trapping of silt released from melting ice lenses on a rotating detrital grain during slope transport by solifluction. Plane polarized light, horizontal frame length 3 mm

limits are exceeded. Near-surface sediments are displaced downslope more rapidly than the sediments at depth, producing a concave downslope displacement profile. This phenomenon has been measured in the laboratory (Harris *et al.*, 1993) and in similar solifluction features in Okstindan (Figure 1, and Harris 1977). Near-surface sediments from upslope therefore probably dam up behind the vegetation mat forcing the lobe to roll over, and thereby invert the soil profile. Similar inverted podzolic soils associated with solifluction have been observed in the Austrian Alps (H.Veit, pers. comm.).

Although the lobe stratigraphy is highly suggestive of this mechanism (Figure 2), if the trench section really is inverted, one would expect that an inverted micromorphological profile would be encountered at the base of the Bhs and in the Eab horizons. If found, this would negate the possibility that the Eab horizon represented the remains of a soil formed during a previous phase of pedogenesis.

MICROFABRIC RESULTS

Silt cappings which encircle detrital grains are occasional to frequent (2–50 per cent coverage) in thin sections from the near-surface (0–15 cm) solifluncted Ea and Bhs horizons (Figure 5). At mid-depth (15–25 cm) in the Bhs horizon, silt cappings are usually only found on the upper surfaces and occasionally side surfaces of grains. Below this level (25–35 cm) in the Bhs horizon, the silt cappings are best developed on the bottom and occasionally side surfaces of grains (Figure 6). Very occasionally, a top surface capping was encountered at this level but was usually very thin (< 200 μm) and poorly preserved. In the base of the Bhs horizon (*c*. 40 cm below the lobe surface) and in the Eab horizon, encircling silt cappings are, once again, the dominant microstructure (Figure 6).

All cappings observed have very sharply defined smooth outermost surfaces. The capping materials are smaller than very fine sand (< 125 μm) but there is a distinct lack of clay-sized sediment. Most cappings display small-scale normal grading structures, with coarse detrital grains and even small lithic fragments resting directly upon the surfaces of large (> 500 μm) lithic fragments, detrital minerals or soil aggregates. These give rise to a marked flecked extinction when observed under crossed polarizers. The intact nature of the capping materials and aggregates is probably due to cementation by iron oxides. Where large accumulations of silt have produced thick (500 μm) cappings, some have become detached from their host grains (Figure 6). These are generally well-rounded to rounded and again possess sharply defined smooth surfaces.

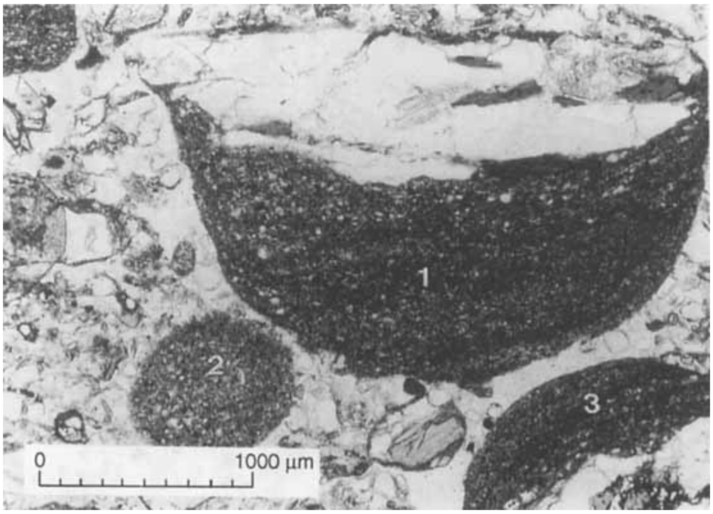

Figure 6. Thin section photomicrograph of a thick silt capping (1) located on the bottom surface of an elongate lithic fragment. Note also the presence of a circular concentration feature (2), formed of capping material that has become detached during grain rotation. The top of an encircling silt cap is also visible (3) at this depth in the profile. Plane-polarized light, horizontal frame length 3 mm

Cappings occur on grains of all shapes, but are best on blade- and rod-like particles. The cappings also exhibit fine laminations which generally follow the surface morphology of their host grains (Figure 7). This specific laminated character may result from successive annual accumulations of fine matrix material.

In addition, there is an abundance of fractured biotite-mica sheets and lithic fragments of mica-schist in the podzolic soils of Okstindan. The orientation of these large fragments is generally between 0 and 30° from the horizontal and is characteristic of solifluction sediments in the area (Harris and Ellis, 1980). Another

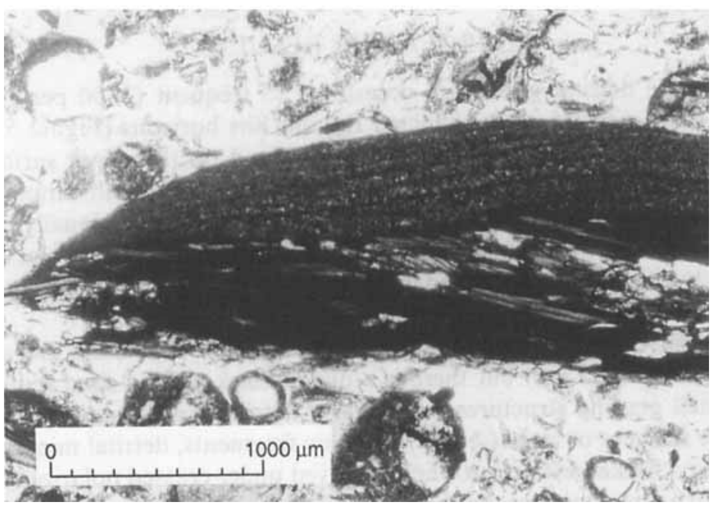

Figure 7. Thin section photomicrograph of a streamlined, finely laminated top surface silt cap. Plane-polarized light, horizontal frame length 3 mm

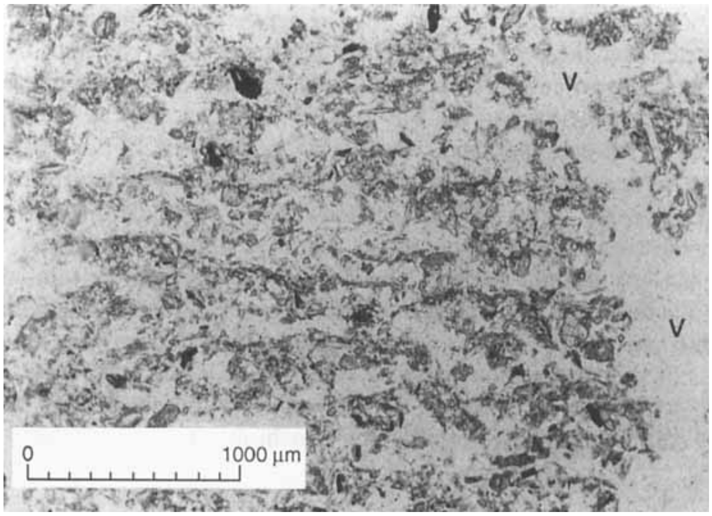

Figure 8. Thin section photomicrograph of a banded fabric which testifies to a legacy of segregated ice formation. Note the granular texture and large voids (V). Plane-polarized light, horizontal frame length 3 mm

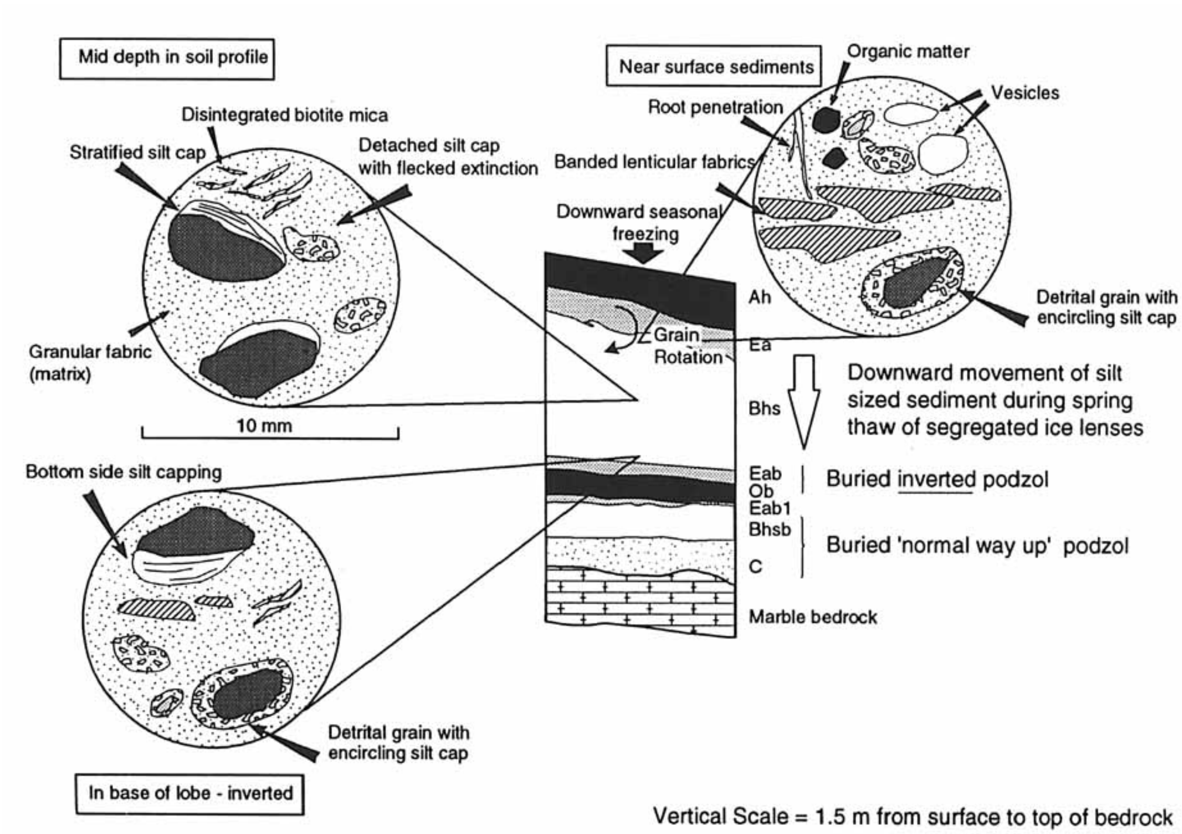

Figure 9. Schematic diagram to illustrate the characteristic cryogenic microstructures observed in humo-ferric podzols affected by solifluction in Okstindan, north Norway. Note the abundance of encircling silt caps in the surface and base of the solifluction unit, and only top-side and bottom-side caps at mid-depths. The soil profile is 1·0 m from the soil surface to the base of the till

notable feature observed in the thin sections from the near-surface sediments is a banded fabric which testifies to a legacy of ice segregation (Figure 8). At mid-depths in the Bhs horizon, no banded fabric was observed which illustrates that there was a lack of ice lensing at this level and, by inference, a reduction in the rate of solifluction. The potential for grain rotation and the formation of encircling silt caps at this depth is therefore reduced. At the base of the Bhs horizon, however, a weak banded fabric is preserved in association with encircling silt cappings and cappings formed on the bottom surfaces of detrital grains. This suggests that these were once in a near-surface position, prone to ice segregation processes, and have subsequently been inverted. No birefringence fabrics were observed in the thin sections. This is to be expected given the very low quantities of clay in the sediment samples (Figure 3). Similarly, the presence of vesicles in the thin sections was not evident. This is probably because the samples were collected in late summer and therefore at a time when the sediment would have consolidated. It is unlikely that vesicles would survive during this phase, particularly as they are considered somewhat transient in nature (Harris, 1985). In summary, observations of soil thin sections have revealed the presence of an inverted micromorphological profile which is shown schematically in Figure 9. This supports the notion that the podzol soil has been inverted by downslope solifluction in a caterpillar-track fashion.

DISCUSSION

The formation of silt cappings was discussed by Van Vliet-Lanoë (1982, 1985, 1987, 1988). She contended that the type of microfabric could be classified according to four styles of mass movement. Type I microfabrics are dominated by silt cappings on the upper surfaces of grains and are formed by frost creep at sites where the moisture supply is limited. The type II microfabric comprises upper surface cappings and encircling cappings. The mass movement process responsible for its formation is transitional between frost creep and gelifluction. The process is faster and occurs where the soil moisture supply is greater. The type III microfabric is composed predominantly of encircling silt cappings and is restricted to the process of gelifluction. It occurs as a result of soil saturation from melting ice lenses and late-lying snow during the thaw phase. Type IV microstructures are restricted to mudflows and skinflows. Following these criteria, the abundance of encircling cappings (type III) in the near-surface soil horizons and in the base of the Bhs and Eab horizons at the solifluction site in Okstindan suggests that gelifluction was responsible for their formation. At mid-depths, where encircling cappings are extremely infrequent or not encountered, the sediment probably moved only very slowly by frost creep (type II). Evidence for active gelifluction in the near-surface and in the base of the lobe, but not at mid-depths, appears only to be adequately explained if the lobe sediments roll-over.

It is probable that the lack of encircling silt cappings at mid-depths in the soil profile is due to the fact that the soil is frozen (and therefore stable) for longer than the near-surface sediments during the spring thaw. More moisture is available in the near-surface which increases the pore water pressures and induces solifluction in these sediments. When the sediment at depth thaws, the excess moisture in the soil rapidly drains which promotes slope stability and simultaneously reduces the likelihood of grain rotation. Without this rotational component it is difficult to envisage how encircling silt cappings can form. This notion is supported by measurements of soil displacement made by Harris (1974, 1977; Figure 1) which showed a marked reduction in soil displacement with depth. This was a function of the rate and amount of frost penetration which, although it may vary with soil depth, probably depends to a large degree on snow cover thickness.

Recent theoretical and empirical research on deformation-induced microstructures in solifluction sediments by Bertran (1993) also illustrated the presence of 'matrix coatings' around detrital grains. Bertran (1993) suggested that these microstructures were the result of stresses induced at the grain–matrix interface during rotation in the thaw phase. He noted that encircling silt cappings were only present on equidimensional particles because these would rotate indefinitely during progressive deformation (as in solifluction) while particles with larger axial ratios tend to stabilize at a critical orientation close to the sliding plane. Thus, he contended that grains with larger axial ratios possess silt cappings on their upper surfaces only. Further, he suggested that the changing nature of deformation during thaw of the sediment from

heterogeneous (concentrated along planes) to homogeneous (distributed throughout profile) shearing would also contribute to the marked spatial distribution of encircling silt cappings in the soil profile.

The proposal that rotation of grains and formation of the encircling silt cappings is favoured during the thaw phase of the sediment, when excess pore water pressures promote viscous flow conditions, is substantiated by the Okstindan sediment grain size and liquid limit data. It is suggested that silt-sized sediment released from melting ice lenses moves down through the soil profile, becoming trapped on larger detrital grains (Figure 9). At this time, grain rotation allows continual trapping of this sediment on all sides, producing the encircling silt cappings. However Bertran's (1993) contention that the encircling silt cappings are found *only* on equidimensional grains is not supported by the Okstindan data. In the Okstindan podzols, encircling silt cappings are found on blade- and rod-like grains as well as on more equidimensional particles (Figure 5). Moreover, the better development of cappings on blade- and rod-like grains suggests that they possess a greater sediment trapping potential than grains of other shapes. A factor which perhaps explains the differences between Bertran's data and that presented here is that the Atterberg limits (Figure 4) of the Okstindan samples are much lower. This is primarily a function of the very low clay content in all of the samples tested (Figure 3). The mobility of the Okstindan sediments during the spring thaw would thus be much greater, thereby enabling easier rotation of detrital grains of all shapes. In contrast, the clay contents in the samples studied by Bertran were higher. This would restrict the amount of grain rotation, particularly of elongate grains which would tend to stabilize along the principal plane of movement in preference to equidimensional particles.

CONCLUSIONS

Encircling silt cappings around detrital grains appear to form during the spring thaw of the sediment. During this phase, rotation of detrital grains enables continual trapping of silt on all grain faces, which is released from melting ice lenses in the near-surface soil profile. The lobe stratigraphy and the inverted micromorphological profile combined provide evidence for the complete inversion of a podzolic soil by solifluction in a caterpillar-track fashion.

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